Visuo-Spatial Attention in Reading:
Three Approaches Combining Eye Tracking and EEG

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Abstract

Visuo-spatial attention is a key contributor to word processing and oculomotor control in reading. There is a vast amount of behavioral and electrophysiological research about the processing of simultaneously available input in foveal and parafoveal regions of the visual field. Yet, the spatial and temporal dynamics of attention allocation within a fixation remain unclear. The present dissertation uses three approaches in the co-registration of eye movements and EEG to investigate this gap and provide direct, online insights into attention distribution across fovea and parafovea, its adaptation to processing load and saccadic behavior, as well as its effects on word processing. In Study 1, the probe paradigm was implemented as a mapping tool of spatial attention adaptation to foveal and parafoveal word processing in the absence of eye movements, yielding ERPs. Behavioral results showed that parafoveal words can be completely processed while maintaining fixation on another word. The enhanced probe-related N1 in-between trials indicates a recruitment and redistribution of additional resources to achieve this task. Study 2 tested the electrophysiological correlate of the preview benefit and its modulation by saccades and foveal load in word list reading, thereby aiming at establishing this correlate as an indirect index of parafoveal attention allocation in ERPs and FRPs. There was a robust effect of orthographic preview on the N1 that was stronger in saccadic reading compared to RSVP and smaller after fixating difficult compared to easy words, indicating underlying attention effects. In Study 3, two independent datasets (Study 2 and another similar word list reading experiment) were reanalyzed with regard to the lateralization of oscillatory activity in the alpha-band in order to directly support the assumptions regarding attention generated in Study 2. Alpha was more strongly right-lateralized in saccadic reading compared to RSVP, and moment-to-moment lateralization predicted shorter subsequent fixation duration, emphasizing the role of parafoveal attention allocation and its relation to saccades. Despite the limitations of the three approaches at this point, the combination of eye movements, ERPs, FRPs, and EEG oscillations provides suitable online markers of attention processes in word recognition that complement traditional research methods.

Zusammenfassung

Visuell-räumliche Aufmerksamkeit spielt eine Schlüsselrolle in der Wortverarbeitung und der Kontrolle von Augenbewegungen beim Lesen. Es liegt eine beachtliche Menge an Verhaltens- und elektrophysiologischer Forschung über die Verarbeitung von zeitgleich verfügbarer Information in fovealen und parafovealen Regionen des visuellen Feldes vor. Dennoch bleibt die räumliche und zeitliche Dynamik von Aufmerksamkeitsbereitstellung innerhalb einer Fixation bisher unklar. Die vorliegende Dissertation nutzt drei Ansätze in der Ko-Registrierung von Augenbewegungen und EEG um diese Forschungslücke zu beleuchten und direkte Einblicke in die Verteilung von Aufmerksamkeit zwischen Fovea und Parafovea, ihre Anpassung an Verarbeitungsansprüche und Augenbewegungen sowie ihre Auswirkungen auf Wortverarbeitung zu liefern. In Studie 1 wurde das Probe Paradigma als Hilfsmittel zur Abbildung räumlicher Aufmerksamkeit in fovealer und parafovealer Wortverarbeitung ohne Augenbewegungen implementiert. Verhaltensdaten zeigten auf, dass parafoveale Worte vollkommen verarbeitet werden können, während ein anderes Wort fixiert wird. Die vergrößerte, Probe-bezogene N1 zwischen einzelnen Wortpräsentationen deutet auf eine Bereitstellung und Umverteilung zusätzlicher Ressourcen hin, um dieser Aufgabe gerecht zu werden. Studie 2 untersuchte das elektrophysiologische Korrelat des Preview Benefits und seine Modulation durch Sakkaden und foveale Verarbeitungsschwierigkeit in Wortlistenlesen und zielte dabei darauf ab, das Korrelat als indirektes Maß für parafoveale Aufmerksamkeit in ERPs und FRPs zu etablieren. Es zeigte sich ein robuster Effekt des orthographischen Previews auf die N1, der im sakkadischen Lesen stärker war als in RSVP und schwächer nach der Verarbeitung schwieriger im Vergleich zu leichten Wörtern. Dies impliziert, dass dem Preview Effekt Aufmerksamkeitseffekte zugrunde liegen. In Studie 3 wurden zwei unabhängige Datensätze (Studie 2 und ein weiteres, ähnliches Wortlisten-Experiment) hinsichtlich der Lateralisierung von oszillatorischer Aktivität im Alpha-Band untersucht um die in Studie 2 bezüglich Aufmerksamkeit generierten Hypothesen zu unterstützen. Alpha war im sakkadischen Lesen stärker rechts-lateralisiert als in RSVP und eine stärkere Lateralisierung sagte eine kürzere Dauer der nachfolgenden Fixation vorher, was die Rolle von parafovealer Aufmerksamkeit und ihre Verbindung zu Sakkaden betont. Trotz der Einschränkungen dieser drei Ansätze zum jetzigen Zeitpunkt stellt die Kombination von Augenbewegungen, ERPs, FRPs und EEG-Oszillationen geeignete, direkte Maße für Aufmerksamkeitsprozesse in der Wortverarbeitung dar, die traditionelle Forschungsmethoden sinnvoll ergänzen können.

SYNOPSIS

1 Introduction

In modern society, a lot of information is exchanged in written form. Rather than making a phone-call, watching the news on TV, or purchasing a train ticket at the counter, we fall back on texting, chatting and mailing, we read news on the internet, and buy tickets at automatic transaction machines. Cellphones, tablets, laptops – there are numerous devices for communication that surround us and rely on the user to be able to read. As a consequence, the crucial skill of reading is now more important than ever.

In contrast to spoken language, the written language is static, that is, more than one linguistic symbol is present at a time, waiting to be identified before the reader reaches the end of a sentence. This puts the reader in control of the flow of information extraction. We move our eyes along lines of text by mostly following the word order, convert visual features into orthographic and phonological patterns, identify words, and integrate them into larger structures (Rayner & Pollatsek, 1989). Despite the complexity of this process, we seem to accomplish this daily task effortlessly. The aim of reading research is to understand *how*.

For the past four decades researchers have discussed about what we actually perceive when reading, how bits of that perceived information interact, what guides our eye movements, and what exactly happens during the resting periods in between. While a vast amount of studies at the behavioral and psychophysiological level have contributed to the investigation of these topics, a gap remains at their intersection: the processing of simultaneously available input *within* a fixation. In this context, a key contributor in need of exploration is visuo-spatial attention.

This dissertation uses three different approaches based on the co-registration of EEG and eye movements to investigate the temporal and spatial dynamics of foveal and parafoveal attention allocation in reading: event-related potentials (ERPs), fixation-related potentials (FRPs), and continuous EEG activity. First, I provide a theoretical background on information extraction within the visual field. This is complemented by a brief summary of the mechanisms of attention and their application to reading. Third, I give an overview over models of serial and parallel attention allocation. Last, the three approaches that arise from the theoretical background, their implementation in three studies, and implications for attention dynamics in reading are summarized.

1.1 The Perceptual Span

In reading, the reader's eyes move along the text in a quick alternation of eye movements (*saccades*) and resting periods (*fixations*) that typically last about 250 ms (Miellet, O'Donnell, & Sereno, 2009). Even though saccades do not serve information uptake themselves due to trans-saccadic suppression of visual input (Matin, 1974), they play a principal role in reading: Three to four times per second, they move new information into the central 2° of vision, called *fovea* (Schotter, Angele, & Rayner, 2012). Here, visual acuity is highest, whereas it drops off sharply towards the edges of the visual field, referred to as *parafovea* (2-5°) and *periphery* (> 5°). The region of vision where perception is still effective is commonly referred to as the *perceptual span*.

While processing efficiency within the visual field is closely linked to visual acuity, there are several reasons to interpret the perceptual span as being governed mainly by attentional mechanisms. First, the size of the perceptual span is best described in letter spaces rather than visual angle because the number of letters crossed by a saccade is relatively fixed, even if the letters subtend different visual angles (Morrison & Rayner, 1981). Moreover, if the decline in visual acuity is compensated for by magnifying each letter with its eccentricity, the number of letters covered by the perceptual span remains constant (Miellet et al., 2009). Second, in extending three letters to the left of the fixation location and 14 letters to the right in the English language (McConkie & Rayner, 1975, 1976), the perceptual span only extends horizontally (Inhoff & Briihl, 1991), and – in contrast to the symmetric decrease in visual acuity – is asymmetrical, favoring word recognition in the right visual field (Ducrot & Grainger, 2007; for a review see Ellis, 2004; Simola, Holmqvist, & Lindgren, 2009). This asymmetry adapts to reading direction. It is reversed for Hebrew readers (Pollatsek, Bolozky, Well, & Rayner, 1981) and rotated vertically in Japanese (Osaka, 2003). Third, the size of the perceptual span varies as a function of interindividual factors such as reading speed (Rayner, Slattery, & Belanger, 2010) and reading skill (Rayner, 1986; Rayner, Murphy, Henderson, & Pollatsek, 1989), but also on an intraindividual level due to processing difficulty (Inhoff, Pollatsek, Posner, & Rayner, 1989). Lastly, it is smaller for orthographically densely packed writing systems (Rayner, 1998).

Notably, the perceptual span covers multiple words in the visual field at a time, meaning that information is not only extracted from the currently fixated word, but also from words located in the parafovea. It has been shown that parafoveal single letters, letters within words, and even whole words can be identified when shown in isolation (Bouma, 1970, 1973; Rayner & Morrison, 1981; Schiepers, 1980), even though lexical processing slows down with increasing eccentricity (Lee, Legge, & Ortiz, 2003). That being said, it is difficult, if not impossible, to *read* based on parafoveal information alone (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). In fact, the *identification span*, that is, the area from which words can be completely identified, is smaller than the perceptual span and usually does not reach further to the left than the beginning of the fixated word (Rayner, Well, & Pollatsek, 1980) and further to the right than seven to eight letters (Rayner, Well, Pollatsek, & Bertera, 1982). Thus, most words have to be fixated to be reliably identified (McConkie, Zola, Blanchard, & Wolverton, 1982). Still, there is vast evidence that readers obtain partial-word information from the parafovea and use this information to improve their processing efficiency. The focus of the next section is a brief overview over this body of evidence.

1.2 Parafoveal Processing of Words

Readers fixate only about 70% of words in a text directly, skipping the other 30% (Schotter et al., 2012) while still comprehending the sentence. Most of those 30% are skipped because they are short (Rayner & McConkie, 1976), or predictable from the context (Rayner, Slattery, Drieghe, & Liversedge, 2011; Rayner, White, Kambe, Miller, & Liversedge, 2003). Regardless, if a word is skipped, the necessary lexical processing to conclude its meaning must have occurred in parafoveal vision.

There are several indications of how much readers use foveal and parafoveal information that are based on manipulating the amount of information available from the two sources. Firstly, McConkie and Rayner (1975) introduced the *moving-window paradigm* that restricts the visibility of information surrounding the fovea. The reader's eyes are monitored and text outside the pre-defined window around the current fixation position is replaced by other letters. Secondly, Rayner and Bertera (1979) used the *moving-mask paradigm* as a reversed equivalent to the moving window. Here, foveal letters are masked while parafoveal and peripheral information remains visible. Thirdly, in the *gaze-contingent boundary paradigm* (Rayner, 1975), single critical words (*target*) in a line of text are altered or masked and become visible once the reader's eyes cross an unseen boundary in front of the target.

The application of the first two paradigms led to the following findings: As one would expect from the sharp decrease in visual acuity, reading efficiency drops swiftly if a moving mask covers the entire fovea, and almost no information about a sentence is obtained if only peripheral vision is unrestricted (Fine & Rubin, 1999a, 1999b; Rayner & Bertera, 1979). Then again, parafoveal vision is still very important for reading efficiency. As

Blanchard, Pollatsek, and Rayner (1989) summarize, a small moving window leads to decreased reading speed – even though, theoretically, little information has to be processed and the eyes could move on more quickly. Quite the contrary, since the restricted window hinders parafoveal preview of the next word, this information cannot be utilized to facilitate subsequent foveal processing (Rayner et al., 2003).

With regard to the boundary paradigm, there have been two key effects for parafoveal information uptake. First, the amount and type of information available for a parafoveally presented word (called *n*+1) during the fixation on the foveal word *(n)* can influence the subsequent processing of *n*+1, which is referred to as the *preview benefit*: Fixation durations on *n*+1 are 20-50 ms shorter if it had been parafoveally visible compared to if it had been masked. Second, processing of *n*+1 can influence the processing of *n*, which is referred to as *parafovea-on-fovea effect* (POF). For example, fixation durations on *n* are inflated if *n*+1 contains illegal letter combinations (Drieghe, 2011; Starr & Inhoff, 2004), indicating that some orthographic parafoveal processing occurs simultaneously to foveal processing. However, POF effects are not the focus of this dissertation and are only mentioned for the sake of completeness. The effect of interest in the following is the preview benefit.

By manipulating certain features of the mask that determine the visual, orthographic, phonological, or semantic relation between mask and target, one can investigate the level of parafoveal information extraction. Differences between languages and writing systems aside, the preview effect has been shown to be independent of visual features (McConkie & Zola, 1979; Rayner, McConkie, & Zola, 1980). There is evidence for phonological (Pollatsek, Lesch, Morris, & Rayner, 1992) and morphological effects (Deutsch, Frost, Pollatsek, & Rayner, 2005), but these effects depend on the connection between orthography and phonology, as well as whether the investigated language is analytic or synthetic, respectively. Furthermore, the preview benefit has been found on a semantic level (Hohenstein, Laubrock, & Kliegl, 2010; Schotter, 2013; Yan, Richter, Shu, & Kliegl, 2009), but not consistently (Rayner, Balota, & Pollatsek, 1986). The most often replicated finding, however, is an orthographic preview benefit (Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005; Inhoff, 1987, 1989a, 1989b, 1990; Inhoff & Tousman, 1990; Lima & Inhoff, 1985; Rayner, 1975; White, Johnson, Liversedge, & Rayner, 2008): Parafoveal visibility of the word-initial letters significantly facilitates target processing by enabling the reader to initiate lexical access.

Importantly, the findings by Inhoff (1989b) underline once more that not visual acuity, but attention is the determining factor for parafoveal preprocessing. The orthographic preview benefit could be found when reading normally from left to right, but also when reading from right to left, meaning that the word-initial letters are further away from fixation. In addition, McDonald (2006) found a preview benefit only when the incoming saccade from the pre-target word landed on the target, but not if there was a refixation on the pre-target. Since a saccade is preceded by attention allocation to its goal (Deubel & Schneider, 1996; Rolfs & Carrasco, 2012), this finding implies that attention is necessary for parafoveal pre-processing to occur.

And yet, the deployment of attention to the parafovea is dependent on the processing of the currently fixated word *n*. If that word induces high processing load because it is of low frequency and, therefore, its lexical access is difficult (Inhoff & Rayner, 1986; Rayner & Raney, 1996), the preview benefit for the upcoming parafoveal word (*n*+1) is reduced (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999; White, Rayner, & Liversedge, 2005). This is most commonly explained by the *foveal load hypothesis* (Henderson & Ferreira, 1990). Increased foveal processing effort requires more attention, leaving fewer resources to extrafoveal processing. There is some evidence that this dynamic might even cumulate across several adjacent words, although these effects have been discussed critically (for an exchange see Kliegl, 2007; Kliegl, Nuthmann, & Engbert, 2006; Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007). Yan and colleagues (2010) manipulated the frequency of the next word (*n*+1) and the preview of the next but one word (*n*+2) to the right of fixation. Indeed, they found a preview benefit for word *n*+2, but only if word *n*+1 was easy to process. Correspondingly, by manipulating the parafoveal visibility of word *n* and word *n*+2, Wang, Inhoff, and Radach (2009) showed that masking of word *n* diminishes the acquisition of parafoveal information from word *n*+1, and with it the acquisition of information from *n*+2. Along the lines of the foveal load hypothesis, a denied preview increases subsequent foveal load because there is no support from parafoveal preprocessing. As a consequence, the currently fixated word pulls more attentional resources at the expense of parafoveal preprocessing of the next word.

This chain of argumentation alludes to a key factor that needs further consideration: Attention is subject to capacity limits. In order to understand what attention actually is and how it operates, the next section will give a brief introduction to this essential top-down modulating system.

1.3 A Brief Introduction to Visuo-Spatial Attention

The neuronal activity required for cortical computations in visual perception costs metabolic energy (Attwell & Laughlin, 2001) – a limited resource that needs to be handled flexibly. Not all sensory information can be processed, but has to be filtered at the perceptual level via sensory enhancement (e.g., Bashinski & Bacharach, 1980; Heinze, Luck, Mangun, & Hillyard, 1990), noise reduction (e.g., Lu & Dosher, 1998), and efficient selection (for a review see Carrasco, 2011). By increasing the signal-to-noise ratio of neuronal responses, the processing of relevant stimuli within a restricted region of the visual field is improved. At the same time, the baseline activity for processing the remainder of (irrelevant) information is decreased. This *sensory gating* (Hillyard & Anllo-Vento, 1998; Hillyard & Mangun, 1987; Posner, 1980) is the underlying mechanism of what has been likened to a spotlight (Posner, Snyder, & Davidson, 1980), a zoom lens (Eriksen & St. James, 1986), or a Gaussian gradient (Downing & Pinker, 1985) – namely top-down visuo-spatial attention.

Attention can be divided into an involuntary and a voluntary system (Carrasco, 2011). The former, referred to as *exogenous attention*, relates to an automatic orienting response to sudden stimulus occurrence. Its temporal nature is transient, meaning that attention allocation rises and declines quickly (e.g., Remington, Johnston, & Yantis, 1992). The latter, referred to as *endogenous attention*, corresponds to a willful monitoring of information that can be sustained for as long as needed. Moreover, attention can be allocated to relevant stimuli either overtly, that is, by foveating stimuli through head or eye movements. Or, it can be allocated covertly, that is, by attending to extrafoveal regions of the visual field while the eyes remain stable. Either way, attention and saccades are closely coupled in a mutually beneficial relationship, such that pre-saccadic attention shifts to a spatially-extended region around the saccade goal improve perception and select possible landing sites (for a review see Kowler, 2011).

The essential control circuitry for attention consists of a network including the dorsolateral prefrontal and posterior parietal cortex that controls the signal transmission in the geniculate-striate pathway (Hillyard & Anllo-Vento, 1998). This top-down modulation of short-latency activity in the primary visual cortex becomes evident in visual-evoked potentials (VEPs). In comparison to unattended stimuli, stimuli located within an attended area elicit an enlarged positive and negative electrophysiological response around 100 ms (P1), 170 ms (N1), and sometimes even 220 ms (P2) in occipital-parietal cortex, as has been repeatedly shown in spatial cueing studies (e.g., Handy & Khoe, 2005; Heinze et al., 1994; Hillyard & Anllo-Vento, 1998; Luck, Heinze, Mangun, & Hillyard, 1990; Posner, 1980; Trejo, Kramer,

& Arnold, 1995). The stimuli used have mostly been simple, isolated items that needed to be detected or categorized. With regard to linguistic material, the effects of attention become a little more complex.

There certainly are parallels between the attentional modulation of perceptual and linguistic processes since words have perceptual properties. Yet, words also hold symbolic properties that are elements of a structured system (Van Petten, 2014). Therefore, questions raised about attentional operations on word recognition are multilayer. “How does visuo-spatial attention influence higher-level processing? Can attention be tuned to semantic features? What role does processing load play?” – To name a few. Some, but not all, of these questions have been addressed in reading research and led to interesting findings. For example, attention can indeed be semantically oriented and, thereby, modulate post-perceptual processing stages (Cristescu & Nobre, 2008). However, it is beyond the scope of this dissertation to address those latter aspects of the wide attentional repertoire that go beyond visuo-spatial attention.

1.4 How Attention Operates in Reading

Regarding the neural processing of words, only a limited number of studies have investigated the modulatory effects of visuo-spatial attention (e.g., Bentin, Kutas, & Hillyard, 1995; Cristescu & Nobre, 2008; Dell'Acqua, Pesciarelli, Jolicour, Eimer, & Peressotti, 2007; McCarthy & Nobre, 1993; Zhang & Zhang, 2007). It is undisputed that attention is inherently linked to lexical processing (McCann, Folk, & Johnston, 1992; Rayner & Pollatsek, 1989), and interacts with word identification in various ways. It modulates orthographic information uptake and subsequently accelerates the connection between lexical and semantic information (Stolz & McCann, 2000). These enhancing effects can be found from early visual up to higher-level post-perceptual processing. For example, besides investigating the abovementioned semantic attention, Cristescu and Nobre (2008) also investigated visuo-spatial attention effects and observed the early effect to be reflected in increased P1 amplitudes for spatially attended versus unattended words. The later effect showed in a more negative amplitude around 400 ms over centro-parietal sites for attended versus unattended targets (N400; see also Bentin et al., 1995; Miniussi, Marzi, & Nobre, 2005). Similarly, McCarthy and Nobre (1993) found that the typically observed semantic-relatedness effect on the N400 (the amplitude is larger for unrelated compared to related words) only occurs if word pairs are presented on the attended side of the visual field. Even if two words are successively presented at fixation, the sustained upholding of attention in a *hold/release paradigm* (i.e., either the first, or the first and second word need to be attended for the accomplishment of the task) enhances both the N1 amplitude and the P3 amplitude which is considered an index of working memory updating (Martin, Thierry, & Demonet, 2010). In contrast, the authors found the P3 component locked to the second word to be absent if attention is released.

Hence, perceptual effects of attention seem to cascade through successive cognitive stages (Ducrot & Grainger, 2007). In doing so, attentional selection based on location has temporal priority in the sense of an early spatial filter (Anllo-Vento & Hillyard, 1996). Interestingly though, visuo-spatial attention effects are not necessarily unidirectional, but can interact with mechanisms that mediate lexical or semantic access. As Dell'Acqua et al. (2007) showed, the N2pc, an increased negativity over contralateral compared to ipsilateral posterior sites that is sensitive to spatial attention allocation, is attenuated when an attended target and an unattended distractor are semantically related rather than unrelated. The authors assume that signals from a rapid initial semantic analysis can be fed back to posterior visual areas, and fed forward to ventral-occipital and inferior-temporal areas where they bias spatial attention allocation.

To conclude, readers are clearly able to actively influence the processing of both foveally as well as parafoveally presented words when attending to them individually. However, in reading, information in need to be handled is available in the fovea and the parafovea at the same time. As mentioned above, those two types of information interact. In other words, the processing of adjacent words in a line of text is not independent. The temporal and spatial dynamics of attention allocation to fovea and parafovea remain unclear, however. In this regard, two opposing types of reading models have expressed two assumptions: serial and parallel attention allocation, respectively.

1.5 Models of Serial and Parallel Attention Allocation

On the one hand, “sequential attention shift” (SAS) models postulate serial attention shifts from one word to the next. Attention is focused on the fixated word *n,* which is processed selectively to a certain extent, and only shifts to the parafoveal word *n*+1 once a higher processing level of *n* is reached (Morrison, 1984). To illustrate: The most prominent SAS model, E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006; Reichle, Tokowicz, Liu, & Perfetti, 2011; Reichle, Warren, & McConnell, 2009), hypothesizes an early stage of visual analysis (V) that occurs parallel across all the words within the perceptual span. Thereafter, there are two stages of lexical processing, L_1 and L_2, which are accompanied by two stages of saccade programming. L_1 constitutes cursory processing, similar to a familiarity-check on a pre-attentive level. Once finished, a saccade to *n*+1 is programmed. L_2 is the more thorough processing stage of lexical completion. If it terminates before the next saccade to *n*+1 is executed, attention shifts covertly from *n* to *n*+1 and initiates lexical preprocessing. Put differently, the narrow spotlight of attention needed for lexical processing can only be shifted once initial processing of *n* is complete, causing attention allocation to fovea and parafovea to work *serially*.

On the other hand, "guidance by attentional gradient" (GAG) models argue that attention allocation is parallel, and is shared among foveal and parafoveal words (Schiepers, 1980). The most prominent GAG model is SWIFT (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012). It is based on a dynamically changing activation field that necessarily involves spatially distributed processing. In other words, attention can be spread as a gradient across several words in the perceptual span which enables *simultaneous* processing of multiple words. Attention is allocated most strongly to the fovea, dropping off gradually with increasing eccentricity skewed into reading direction. The expansion of the gradient is a function of linguistic processing and, therefore, it is adaptive to processing difficulty of the foveal word. Each word within the gradient has an activation level that represents the degree to which a word has been identified and serves as a saliency map for possible saccade goals.

There are two approaches to distinguish between these two assumptions: (1) investigating whether adjacent words can be processed on the same processing level simultaneously, and (2) directly mapping attention. The focus of this dissertation is on the latter. So far, the distribution of attention postulated by these two types of models has mainly been investigated at the behavioral level, that is, in eye movement studies. However, measurements of gaze position are separated into fixations, and fixation durations only present the behavioral outcome at the close of a chain involving several processes. Consequently, insights into individual processes within that chain and into ongoing underlying brain processes *during* these fixations are only indirect. There have been some complementary contributions on the psychophysiological level from ERP-studies, offering more direct, online insights. Contrary to behavioral studies, however, traditional ERP studies usually present only one word a time at unnaturally long presentation rates in order to avoid corneo-retinal artefacts and temporal overlap in the EEG signal. The aim of this dissertation is to combine both research areas in order to investigate the spatial and temporal dynamics of attention allocation within a fixation. The benchmark phenomena and paradigms useful for this endeavor will be described in the following, along with the summary of each implementation in turn.

2 The Present Studies

2.1 Study 1

2.1.1 The Probe Paradigm

Based on the assumption that processing of stimuli within the locus of attention is enhanced, numerous researchers have presented briefly-flashing light-stimuli, known as *probes*, at certain regions of the visual field that are expected to be attended or unattended, respectively. It has been shown repeatedly that the typically observed VEPs are increased in amplitude when locked to the onset of attended probes compared to unattended ones (Handy & Khoe, 2005; Heinze et al., 1994; Hillyard & Anllo-Vento, 1998; Luck et al., 1990). Neither the probes' relevance for the task, nor their presentation mode affect this result, which underlines that attention selection based on location can occur on a very early processing stage (Hillyard & Anllo-Vento, 1998; Luck et al., 1990). Therefore, it seems possible to map the spatial attention distribution during a task with simultaneous or interim presentation of probes.

The attention tasks that participants are most commonly required to perform are focusing on certain regions of the visual field (Eimer, 1999; Heinze et al., 1994; Hillyard & Anllo-Vento, 1998; Luck et al., 1990), or orienting towards these regions (Handy & Khoe, 2005; Handy & Mangun, 2000). While the to-be-attended area is usually determined by an external spatial cue, it can also be determined by more internal factors. By increasing the number of items that need to be perceived, or by making their perception more demanding, the size of the attended area can be manipulated (Lavie, 2005). This *perceptual* foveal load hypothesis can be understood as equivalent to the aforementioned *lexical* foveal load hypothesis. If perceptual load is high, parafoveal irrelevant stimuli are less likely to be perceived (Lavie, 1995, 2006, 2010), indicating that the spatial attention window around the target contracts with increasing processing difficulty. Accordingly, the P1 elicited by parafoveal probes is reduced under high compared to low foveal load (Handy & Mangun, 2000; Handy, Soltani, & Mangun, 2001). It has to be noted that load effects are not necessarily restricted to the P1 component, but can lead to a prolonged shift of the ERP (Heinze et al., 1990; Luck et al., 1990; Moriya & Nittono, 2011), or can be reflected solely in N1 modulations (Barnhardt, Ritter, & Gomes, 2008; Fu et al., 2008).

Although these studies provide evidence for an influence of foveal load on electrophysiological processes in perceptual tasks, it has not yet been investigated whether this relationship exists in linguistic tasks. Hence, the aim of Study 1 is to apply the probe paradigm to a reading-like setting. As has been shown, isolated parafoveal words can be identified (Rayner & Morrison, 1981), implying that attention is deployed to the parafovea if necessary. In reading however, – similar to the aforementioned perceptual tasks –, stimuli (i.e., words) are available both foveally as well as parafoveally at the same time. Assuming that the parafoveal word is attended to while the word to its left is still fixated, the VEPs elicited by probes presented at the corresponding location could theoretically reflect this attention deployment. Since it is not possible to fixate one target while simultaneously and successfully shifting complete attention to another (Kowler, 2011), it remains unsolved whether a parafoveally presented word can be completely identified under such circumstances. Study 1 therefore investigates foveal and parafoveal processing of words in the absence of eye movements in order to obtain direct evidence for the underlying dynamics of attention.

2.1.2 Summary of Original Article 1

It has been shown in perceptual discrimination tasks that foveal load modulates the attentional span. VEPs elicited by parafoveally presented probes are smaller during difficult foveal tasks compared to easy tasks (for a review see Lavie, 2005). The aim of Study 1 was to investigate the modulation of the attentional span as a function of lexical task load within a fixation. To that end, we applied the probe paradigm to a reading-like situation and manipulated the foveal *and* parafoveal load with the task. Participants were presented with stimuli triplets, consisting of a centrally presented word and a flanker to either side which could be proper words or x-strings. The instruction was to read just the central word or both the central and right parafoveal word of the triplet without making saccades, and make a decision as to whether one of those words was an animal. The spatial and temporal dynamics of attention allocation were mapped by VEPs locked to briefly-flashed, task-irrelevant probes which were presented above the central or the parafoveal positions at three different time points: either 200 or 400 ms into triplet presentation, or in-between trials.

Comparatively high error rates and long reaction times in the "read central and parafoveal" (CP) block indicated that parafoveal targets were hard but possible to identify even in the presence of foveal input. This result complements the finding by Rayner and Morrison (1981) who presented parafoveal words in isolation. In our case, the requirement to attend to the parafovea increased the error rate even for central targets. On the one hand, this could have been caused by a suppression of a saccade towards the parafoveal word as indicated by a rightward shift in eye position within the boundaries of the fixation location. Such a suppression might have used up some processing capacity. On the other hand, it could have been caused by parafoveal-on-foveal interference due to the presence of parafoveal information. This assumption is supported by the finding that reaction times for foveal targets increased when flanked by proper words rather than x-strings even if those flankers were to be ignored, that is, in "read central" (C or X, respectively) blocks. These results serve as evidence that foveal and parafoveal information uptake within a fixation interact.

We did not observe any effects on VEPs elicited by probes during triplet presentation. Firstly, parafoveal probes did not evoke any noticeable VEP, probably due to a non-linear interaction in the ERPs related to triplet and probe presentation, or due to insufficient stimulation at the given eccentricity. Secondly, even though there was the expected VEP pattern for central probes, there was no experimental effect, probably due to the predominant attention allocation to the fovea that is naturally maintained even if some resources are withdrawn to relevant stimuli in the parafovea. However, we did observe experimental effects in the absence of triplets, namely on the inter-trial N1, reflecting an enduring attention modulation. The amplitude of the N1 evoked by central inter-trial probes was increased in reading blocks with flanking words compared to blocks with flanking x-strings, regardless of the reading instruction (i.e., $N1_{CP}$ and $N1_{C} > N1_{X}$), which indicates an increased foveal load as a consequence of linguistic flanker interference. In contrast, the N1 evoked by parafoveal inter-trial probes was increased only in CP blocks and was followed by a long-lasting negative shift of the ERP. The need for spatial coverage when reading foveal and parafoveal words led to a spatial re-distribution of *additional* resources instead of adjusting a *constant* resource supply (Heinze et al., 1990; Luck et al., 1990; Moriya & Nittono, 2011). Such enduring task effects across trials have been reported by Barnhardt et al. (2008), and point to a maintained, high level recruitment of resources and an upheld deployment of attention to the relevant regions of the visual field rather than a fluctuation from trial to trial. The increase in mental effort was further supported by a more pronounced N400 elicited by triplets in CP blocks compared to C and X blocks, an effect that did not stem from context effects, but reflected attentional mechanisms in the active processing of the parafoveal word and its integration with foveal input (Cristescu & Nobre, 2008; Van Petten, 2014).

To sum up, we showed a task-dependent adjustment of attention across trials in the form of an additional, enduring recruitment of resources rather than a reallocation of a limited resource pool.

2.2 Study 2

2.2.1 An Electrophysiological Correlate of the Preview Benefit

Since eye movement studies do not allow inferences about the temporal and spatial dynamics within a fixation, the preview effect and its modulation by foveal load is in accordance with both sequential as well as parallel attention allocation across the visual field. Therefore, psychophysiological data with a high temporal and spatial resolution need to complement eye movement data. So far, there have been two approaches to study how parafoveal preprocessing is reflected in electrophysiological responses. First, in rapid serial visual presentation (RSVP) participants maintain central fixation while one word at a time is centrally presented, yielding ERPs (Barber, Donamayor, Kutas, & Munte, 2010; Barber, van der Meij, & Kutas, 2013; Li, Niefind, Wang, Sommer, & Dimigen, 2015). When placing parafoveal flanker words at each side of the centrally presented word and choosing a quick stimulus-onset asynchrony (SOA) approximating normal reading speed (Dambacher et al., 2012), this RSVP-with-flankers paradigm can account for the quick attention re-allocation to different words within the perceptual span. Second, eye movements and the EEG can be co-registered during natural reading, that is, while moving the eyes freely from left to right across lines of text. When aligning the EEG signal to fixation onsets, this yields FRPs (Baccino & Manunta, 2005; Dimigen, Kliegl, & Sommer, 2012; Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011; Henderson, Luke, Schmidt, & Richards, 2013; Hutzler et al., 2007; Kretzschmar, Bornkessel-Schlesewsky, & Schlesewsky, 2009; Metzner, von der Malsburg, Vasishth, & Roesler, 2015; Simola et al., 2009).

In both approaches, it has been shown that the preview benefit is reflected in the modulation of an occipito-temporal response following the N1 peak (Dimigen et al., 2012; Li et al., 2015). Dimigen et al. (2012) had participants read lists of words including a target word *n* that was either shown in the parafovea (valid preview), that is, during the preceding fixation on its left neighboring word (*n*-1), or masked by another word (invalid preview). Validly previewed targets elicited a smaller negative response between 200 and 280 ms after target fixation than invalidly previewed targets. This effect is referred to as *preview positivity* and has been replicated in Chinese with the RSVP-with-flankers paradigm by (Li et al., 2015).

The left-lateralized N1 elicited by text strings had been interpreted to reflect sublexical (Kutas, Van Petten, & Kluender, 2006) or early lexical processing (Hauk & Pulvermüller, 2004; Sereno, Rayner, & Posner, 1998), as well as orthographic and phonological processing (Maurer, Blau, Yoncheva, & McCandliss, 2010; Maurer, Brandeis, & McCandliss, 2005; Nobre, Allison, & McCarthy, 1994; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). Given that the behavioral preview benefit can be located at the orthographic processing level, there seems to be an overlap between those factors that modulate the behavioral preview benefit and those that modulate the N1. Moreover, the N1 peaks within a typical fixation duration and is early enough to influence motor planning for the next saccade (150 ms; Rayner, Slowiaczek, Clifton, & Bertera, 1983). On these grounds, it presents a suitable electrophysiological correlate of the preview benefit.

There are two important considerations why the preview benefit might also – apart from reflecting word processing – serve as an indirect index of parafoveal attention allocation. First, the preview benefit has been shown to depend on foveal load (Henderson & Ferreira, 1990), indicating that the processing of adjacent words is not independent. The most probable explanation for the interaction of load and preview (i.e., a currently fixated difficult word leads to a smaller subsequent preview benefit than an easy word) is the deployment of the limited resource attention. Consequently, the interaction effect's size reflects the amount of attention allocation to the parafovea. Second, saccades have been shown to influence the occurrence of the preview benefit under certain circumstances (McDonald, 2006). Given that saccades are accompanied by pre-saccadic attention shifts (e.g., Rolfs & Carrasco, 2012), they probably change the deployment of attention between fovea and parafovea and, with it, the preview benefit. Altogether, the aim of Study 2 is to establish the preview positivity as the electrophysiological equivalent to the behavioral preview benefit, and, consequently, as an indirect index of parafoveal attention allocation.

2.2.2 Summary of Original Article 2

ERP research on visual word recognition (e.g., Kutas & Federmeier, 2011) has focused on presenting one isolated word at a time in rapid serial visual presentation that requires participants to maintain constant fixation. Therefore, three key properties of the visual and oculomotor system have been given little consideration: the preprocessing of parafoveally available information (Rayner, 1975), the preparation and execution of saccades (Schotter et al., 2012), and the dynamic, adaptive reallocation of limited attentional resources between fovea and parafovea (Henderson & Ferreira, 1990). Firstly, readers extract partial orthographic and phonological information from the parafovea and benefit from this preprocessing on the subsequent fixation, an effect that has been shown in eye movement behavior (e.g., Rayner, 1975) as well as early (i.e., N1) and late (i.e., N400) electrophysiological correlates (e.g., Dimigen et al., 2012). Secondly, there are only sparse and discrepant results as to whether saccades and the accompanying pre-saccadic shift of visuo-spatial attention enhance

(Marton, Szirtes, & Breuer, 1985) or impair (Temereanca et al., 2012) the uptake of parafoveal information. Thirdly, the processing of adjacent words is not independent since the reader's limited attentional resources need to be dynamically split between them, leading to changes in the efficiency of extrafoveal processing as a function of foveal processing (Henderson & Ferreira, 1990; Lavie, 2005). The aim of Study 2 was to demonstrate the interplay between these factors and their impact on word recognition.

We recorded eye movements and the EEG simultaneously while participants read lists of German nouns in the saccade-contingent boundary paradigm. The task was to detect occasional animal names. We manipulated (a) parafoveal preview, (b) reading paradigm, and (c) foveal load. (a) While the fixated word was always fully visible, the parafoveal visibility of this word during the preceding fixation was manipulated parametrically by leaving no, one, two, three or all letters of the word unmasked and masking the remaining letters with "x". (b) Participants either read the lists from left to right with eye movements (active reading paradigm), or maintained central fixation while the list moved word by word through their field of vision (RSVP-with-flankers paradigm) at a similar speed to active reading. (c) Foveal load was manipulated by varying lexical frequencies of the words in the lists which makes them easy or difficult to process.

In accordance with other reports, preview as well as foveal load affected first fixation durations in active reading (e.g., Henderson & Ferreira, 1990; Rayner, 1975) such that more preview and lower load led to shorter fixations. The preview benefit was attenuated after high compared to low load. With regard to electrophysiological correlates, we firstly observed an effect of preview on the left temporal-occipital N1 component, with the average amplitude between 200 and 280 ms reflecting the number of previewed letters in a perfectly ordinal manner: The amplitude decreased monotonically (*preview positivity*) from no to full preview, which implies a manifestation of orthographic processing in the N1 (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Maurer et al., 2005) and possibly reflects trans-saccadic repetition priming (Dimigen et al., 2012). Given the latency of the effect in active reading (160 ms), the mean fixation duration (309 ms), and the estimated time for saccade preparations (150-175 ms; Rayner et al., 1983), we conclude that the N1 serves as the electrophysiological correlate of the behavioral preview benefit and influences oculomotor behavior. Secondly, the effect was qualitatively similar in both reading paradigms, but was significantly smaller and shorter-lasting in the RSVP-with-flankers paradigm. We assume a facilitatory effect of saccades on foveal, but also parafoveal stimulus processing, amongst other reasons due to pre-saccadic attention shifts (Rolfs & Carrasco, 2012) that did not occur in passive reading. Therefore, saccades change the deployment of attention to fovea and parafovea and affect reading performance. Lastly, the preview positivity was larger after easy than after difficult words. Presumably, processing of a difficult foveal word draws more attentional resources from a limited pool, leaving fewer resources to be deployed to the parafovea (Henderson & Ferreira, 1990). Consequentially, readers cannot benefit from parafoveal previews to the same degree as when foveal processing was less demanding.

In summary, we could show that three properties of natural reading – preview, saccades, and load – substantially impact the neural response to words, the underlying mechanism being attention. Our findings imply that the processing of words extends across multiple fixations. During each of these fixations, neighboring words are attended to and processed in parallel and interactively rather than in temporal and spatial isolation, a process that is facilitated by the execution of saccades.

2.3 Study 3

2.3.1 The Lateralization of Oscillations in the Alpha-Band

On the one hand, while the aforementioned probe paradigm can assess the deployment of attention *directly* while fixating, it is not suitable in contexts of complex stimulation like natural reading that involve eye movements. Additionally to the temporal overlap of fixation-related potentials evoked by consecutive words, there would be a temporal overlap of potentials elicited by probes and words that are difficult to disentangle. On the other hand, behavioral and electrophysiological measures of the preview benefit can only *indirectly* assess the distribution of attention between fovea and parafovea. Therefore, the aim of Study 3 is to map attention allocation in reading more directly by using a suitable marker.

Attention as a top-down control mechanism is omnipresent in the visual system. Not only does it modulate the event- and fixation-related potentials that are averaged across many trials, but also the power and phase of ongoing oscillations in the continuous EEG, particularly in the alpha band between 8 and 14 Hz (for a review see Klimesch, 1999). The dynamic fluctuations between event-related synchronization (ERS) and desynchronization (ERD) of alpha power have been linked to transient as well as sustained attention during the anticipation and processing of a stimulus. This has been shown in various tasks (for a review see Klimesch, 2012), such as word recognition and semantic judgements (e.g., Klimesch, Doppelmayr, Pachinger, & Russegger, 1997), as well as spatial cueing (e.g., Gould, Rushworth, & Nobre, 2011; Worden, Foxe, Wang, & Simpson, 2000). In the latter task, parietal-occipital alpha power has been observed to be larger over recording sites ipsilateral compared to contralateral to the attended hemifield, indicating that alpha power responses are topographically specific. The occurrence of contralateral ERD and ipsilateral ERS is referred to as *alpha lateralization*. ERD and ERS are most prevalently interpreted as facilitated processing of attended locations (Kelly, Gomez-Ramirez, & Foxe, 2009; Rihs, Michel, & Thut, 2009; Sauseng et al., 2005; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Yamagishi, Callan, Anderson, & Kawato, 2008; Yamagishi, Goda, Callan, Anderson, & Kawato, 2005), and inhibited processing of unattended locations (Kelly, Lalor, Reilly, & Foxe, 2006; Rihs, Michel, & Thut, 2007; Rihs et al., 2009; Worden et al., 2000), respectively. Moreover, alpha dynamics related to visuospatial attention may covary with saccadic behavior (Hamm, Sabatinelli, & Clementz, 2012), and pre-saccadic desynchronization has been observed to be strongest contralateral to the saccade goal (Medendorp et al., 2007).

Importantly, alpha lateralization is modulated by task demands: The difference between contralateral and ipsilateral alpha power increases with increasing certainty about the location of the upcoming stimulus (Gould et al., 2011). Also, it increases as the task in the attended hemifield becomes more difficult (Roijendijk, Farquhar, van Gerven, Jensen, & Gielen, 2013). It can be argued from these findings that alpha lateralization directly indexes the variation in voluntary attention deployment to the parafovea. Interestingly, since the momentary deployment of attention predicts behavior and can be estimated from alpha lateralization, the extent of lateralization can, in turn, predict behavior (for a review see Mathewson et al., 2011). Evidence from visual perception tasks shows that pre-stimulus parietal-occipital alpha power is negatively correlated with detection rates, reaction times, and line orientation judgements (Hanslmayr et al., 2007; Hanslmayr et al., 2005; Yamagishi et al., 2008), and can predict performance on a trial-by-trial basis (Ergenoglu et al., 2004; Kelly et al., 2009; Mathewson, Gratton, Fabiani, Beck, & Ro, 2009; Thut et al., 2006; Van Dijk, Schoffelen, Oostenveld, & Jensen, 2008).

So far, only a small number of studies have investigated oscillatory activity in reading (e.g., Kretzschmar et al., 2013; Metzner et al., 2015; Vignali, Himmelstoss, Hawelka, Richlan, & Hutzler, 2016), yet those studies yielded useful results with regard to their matters of interest. Therefore, the aforementioned findings concerning alpha lateralization might be replicable in reading, marking three assumptions about attention distribution: (1) the skewedness of the perceptual span in reading direction, which is probably related to pre-saccadic attention shifts (Deubel & Schneider, 1996; Hoffmann & Subramaniam, 1995; Rolfs & Carrasco, 2012); (2) the stronger allocation of attention to upcoming words in low foveal load situations; (3) more efficient processing of words (i.e., shorter fixation durations) that have received a stronger parafoveal attention allocation on the preceding fixation. All in all, Study 3 is aimed at establishing alpha lateralization as a mapping tool for attention in reading, thereby gathering further knowledge about attention dynamics between fovea and parafovea.

2.3.2 Summary of Original Article 3

Based on findings regarding the behavioral preview benefit in eye movement studies (e.g., Hohenstein et al., 2010; Rayner, 1975) as well as its brain-electric correlate in ERP (Barber et al., 2013; Li et al., 2015) and FRP research (Dimigen et al., 2012; Kornrumpf, Niefind, Sommer, & Dimigen, 2016), it is well-established that word recognition starts before the word itself is fixated. Interestingly, we could show in Study 2 that the preview effect interacts with reading mode (i.e., reading actively or passively) and foveal load during the time course of a fixation. While we assume that attention mechanisms such as its dynamic allocation between fovea and parafovea are the critical factor in these interactions, our inferences are only indirect. Oscillatory activity in the alpha-band of the EEG has been directly related to visuo-spatial attention and saccade preparation in various tasks (Medendorp et al., 2007; Worden et al., 2000). Alpha power typically decreases contralateral to the attended space or saccade goal and increases ipsilateral, resulting in alpha lateralization. Moreover, as a marker for attention allocation, alpha lateralization can predict behavioral outcome on a trial-by-trial basis (Thut et al., 2006).

The aim of Study 3 was to establish alpha power as a new and more direct marker of attention allocation during reading. Following up on Study 2 (in the following referred to as Exp. 1), we re-analyzed our data with temporal spectral evolution (TSE) that yielded an event- and fixation-related alpha lateralization index. To replicate the findings, we also re-analyzed the data from another word-list reading study (referred to as Exp. 2) using a highly similar experimental setup (Niefind & Dimigen, submitted). We had three hypotheses that combined the assumption that rightward alpha lateralization indexes a stronger attentional deployment to the right visual field with our conclusions drawn in Study 2: (1) Rightward alpha lateralization should be stronger in saccadic reading compared to RSVP. (2) High foveal load should result in stronger rightward alpha lateralization than low foveal load. (3) A stronger rightward lateralization before fixation onset should predict a shorter subsequent fixation.

In both datasets, there was a general, sustained rightward alpha lateralization in saccadic reading and no such observable asymmetry in RSVP. This effect of reading paradigm adds to our previous finding that the preview positivity effect on the N1 is much larger in saccadic reading than in RSVP (Kornrumpf et al., 2016; Niefind & Dimigen, submitted). The observed alpha lateralization supports our aforementioned conclusion that there is an attentional bias into reading direction (McConkie & Rayner, 1975, 1976) that is closely linked to saccadic behavior (Van Der Werf, Jensen, Fries, & Medendorp, 2008) and enhances parafoveal processing (Kelly et al., 2009; Thut et al., 2006). In contrast, attentional re-orienting is not required and may even be actively suppressed in RSVP. In line with the much smaller preview effect in RSVP observed in Study 2, we conclude that the symmetry of alpha power reflects a central focus of attention when readers maintain fixation. Moreover, stronger rightward alpha lateralization before fixation onset predicted shorter subsequent fixation duration in both experiments. This serves as further evidence that alpha lateralization indicates attentional processes that determine behavioral outcome from trial to trial (Ergenoglu et al., 2004; Mathewson et al., 2009; Thut et al., 2006). Since there was no interaction of alpha lateralization and preview that would suggest that parafoveal attention allocation is only beneficial if information is indeed parafoveally available, the lateralization supposedly represents general preparatory attentional processes rather than attention-enabled preprocessing. The fluctuations in alpha power have been suggested to occur spontaneously, and to be generated automatically rather than voluntarily as a result of trial-by-trial variability in visuospatial attention (Romei et al., 2008). Lastly, there was no effect of foveal load on alpha lateralization in either experiment. Since load, contrary to reading paradigm, varied from fixation to fixation with no resting periods in between, attention needed to adapt quickly. The temporal resolution of the alpha rhythm could have been too slow to respond to these voluntary changes.

To conclude, we found alpha lateralization to serve as a marker for attention distribution during reading and as a predictor for fixation behavior. The general sustained rightward lateralization in saccadic reading highlights the attentional bias towards reading direction that is absent in RSVP. The larger the lateralization, the shorter is the subsequent fixation, which is presumably due to spontaneous attention fluctuations.

3 General Discussion

The present dissertation combined eye movement- and EEG-recording to bridge the gap between behavioral and electrophysiological reading research with regard to the temporal and spatial dynamics of foveal and parafoveal attention allocation. To that end, I approached the topic from three different perspectives. In Study 1, the probe paradigm was implemented in an ERP design to obtain direct evidence for simultaneous foveal and parafoveal attention allocation. In Study 2, I tested the electrophysiological correlate of the preview benefit as an indirect marker of parafoveal attention allocation in a comparative ERP and FRP design. In Study 3, two datasets (Study 2 and a dataset with a similar experimental setup) were re-analyzed regarding continuous EEG activity in the alpha band to establish alpha lateralization as a direct mapping tool for attention allocation in reading. The results of the three approaches, their implications regarding visuo-spatial attention distribution in reading, as well as their usefulness for future research will be discussed in the following.

3.1 Implications for Attention Dynamics in Reading

3.1.1 Sustained Allocation of Additional Resources to Fovea and Parafovea

While visual information in reading can be most effectively and efficiently processed when located in the foveal field of vision, attention can be deployed to the parafovea in the absence of eye movements, allowing parafoveal word identification (Rayner & Morrison, 1981). The results of Study 1 show that parafoveal words can be fully identified even in the presence of a foveal word. Since it is not possible to shift complete attention to an extra-foveal stimulus while fixating another stimulus at the same time (Kowler, 2011), this finding indicates that attention must have been deployed to fovea and parafovea simultaneously, theoretically allowing parallel word processing. The high error rates for parafoveal word identification and the absence of an experimental effect on VEPs elicited by central intra-trial probes further support the assumption that the predominant attention allocation to the fovea is naturally maintained while only some resources are allocated to the parafovea. Note that the latter statistical null-result has to be viewed critically, of course, and can merely serve as a hint, but not as evidence. Furthermore, the task effects on VEPs elicited by central (the N1 was more pronounced in tasks C and CP compared to task X) and parafoveal (the N1 was more pronounced in task CP compared to tasks C and X) inter-trial probes indicate a sustained recruitment and reallocation of additional resources across trials that spatially cover both foveal as well as parafoveal stimuli, rather than a reallocation of a constant resource pool away from the fovea towards the parafovea.

The experimental design of Study 1 did not allow the inspection of semantic-relatedness or congruity effects on the N400 that have been shown for word triplets before (Barber et al., 2010; Barber et al., 2013), demonstrating parallel semantic processing. Nevertheless, we did make an interesting observation regarding an N400 effect, namely between the task to attend to both foveal and parafoveal words and the task to attend to foveal words alone: The former elicited a stronger N400 than the latter. Similar to the findings by Cristescu and Nobre (2008) as well as McCarthy and Nobre (1993), this result underlines the role of attention in semantic processing and in the integration of parafoveal with foveal information. It has to be noted, though, that the task implemented in Study 1 is highly artificial. Models of serial and parallel attention allocation do not assume the parafoveal word to be completely identified, but only to be preprocessed. Therefore, inferences about parallel attention allocation drawn from the particular task here cannot necessarily be transferred to natural reading. For that reason, I attempted to take the investigation of attention allocation a step further towards reading in Study 2 in order to close that gap.

3.1.2 Inferences from the Interplay between Saccades, Load, and Preview

The results of Study 2 could establish the N1 as the electrophysiological correlate of the behavioral preview benefit. The effect of preview could be located on the falling flank of the slightly left-lateralized N1 which has been linked to processing – specifically of letter strings – at the visual word form area (Cohen et al., 2000). Importantly, this correlate can also serve as an indirect index of parafoveal attention allocation. Since we used word lists that do not allow contextual predictions about the upcoming word, the preview benefit must be based on parafoveal preprocessing which, in turn, requires covert attention. The parametric relationship between the amount of available letters and the size of the preview benefit reflects the usefulness of partial orthographic information in this regard. If parafoveally available orthographic features are identified prior to fixation, this can presumably act as trans-saccadic repetition priming (Dimigen et al., 2012), making subsequent processing faster and less demanding due to efficient mapping from orthography to phonology. Most importantly, both saccade execution as well as foveal load modulated the preview effect.

The most probable underlying mechanism for these modulations is visuo-spatial attention. First, there is a close link between saccades and attention that serves parafoveal processing, amongst other mechanisms via enhanced sensitivity to visual features at the saccade goal (Super, van der Togt, Spekreijse, & Lamme, 2004). Consequentially, attention is allocated to the parafovea more strongly when reading with eye movements than without, resulting in a more pronounced preview benefit. As a side note, it is conceivable that perceptual learning might also exert an influence in this context (Dehaene, Cohen, Sigman, & Vinckier, 2005). The theory states that frequently encountered visual configurations (such as words) in a restricted horizontal region close to the fovea are recognized more efficiently because the regularity of eye movements in life-long reading is associated with visual learning on a low level. Given the role of eye movements in this account, perceptual learning may benefit parafoveal preprocessing in saccadic reading much more than in RSVP. Since preview is also modulated by foveal load, however, an influence of top-down attention appears more essential, even though it does not claim exclusive validity.

Second, since lexical processing of the foveated word requires more or less attentional resources (i.e., the word is more or less difficult), correspondingly extant resources can be deployed to the parafovea. As has been shown in Study 1, the amount of available attentional resources does not have to be constant. Additional resources can be recruited if the task is sufficiently difficult, but this recruitment is probably of a longer-lasting nature, as suggested by the aforementioned sustained effect revealed by inter-trial probes. Nonetheless, since foveal load varied from fixation to fixation and still modulated the preview effect, attention seems to be able to adapt quickly.

3.1.3 Supportive Evidence for Attention Being the Driving Force

To test the assumptions derived from Study 2, we employed a direct marker for the momentary deployment of attention in Study 3: alpha lateralization. Indeed, we found evidence supporting two of our three hypotheses in two similar, but independent datasets. First, alpha was more strongly lateralized to the right in saccadic reading than in RSVP. Second, a stronger alpha lateralization predicted shorter subsequent fixation durations. Regarding the first finding, this serves as direct evidence for our hypothesis that there is a general attention bias in reading direction when reading naturally that is related to the tight relationship between saccades and attention (Rolfs & Carrasco, 2012) and aids preprocessing of upcoming information in a highly overlearned task. In contrast, this bias was suppressed in RSVP due to the task requirement of maintaining fixation. It has to be noted that there was no noticeable change in alpha lateralization within and across fixations, as would be expected in the face of rapid, serial attention shifts proposed by SAS models (Reichle, 2011). Instead, alpha remained right-lateralized to the same degree in saccadic reading, which is comparable to the sustained attention effect in Study 1. In defense of arguing the null-hypothesis in this case, it has to be stressed that the persistence of alpha lateralization across fixations was evident in both Experiment 1 and 2 of Study 3. This cannot likely be attributed to some global underlying adaptation that might conceal occurring shifts because we did indeed observe lateralization changes within the analyzed timeframe under certain circumstances. As mentioned in Study 2, the entire word list was visible in RSVP at all times (apart from the 30 ms breaks in between position changes), being shifted by one position from right to left on each presentation. This might have induced apparent motion and triggered the optokinetic reflex. In other words, participants "followed" the formerly fixated word with their attention towards its next position on the left. This experimentally caused attention shift was reflected in a short-lasting left-lateralization of alpha in Experiment 1. Importantly, the setup of Experiment 2 in Study 3 differed in that regard by only ever presenting three words at a time rather than the whole list, thereby avoiding this reflex. As expected, we observed no change in alpha lateralization here.

Notably, the combined observations from Study 2 and 3 that (a) the size of the preview benefit is smaller in RSVP compared to saccadic reading, and that (b) alpha is right-lateralized in saccadic reading, but not in RSVP, indicate that parafoveal perception is not solely influenced by a directional preference based on reading habits as might be suggested by the often observed lateralized visual field advantage (Ducrot & Grainger, 2007; for a review see Ellis, 2004). The phenomenon reflects a bias to perceive parafoveal information more pronouncedly if it is located on that side of the visual field that is congruent with reading direction. For example, in an RSVP-with-flankers paradigm Barber and colleagues (2011) found a parafoveal congruency effect on the P2 component only if flankers appeared in the right parafovea in English and in the left parafovea in Hebrew, respectively. Their effect resembled the P2 modulation reported by Baccino and Manunta (2005) and Simola et al. (2009) in FRPs, despite the absence of horizontal scanning in their design. Contrary to Barber's (2011) finding, the interaction of reading paradigm with preview, and the effect of reading paradigm on alpha lateralization underline the specific contribution of saccades to attention dynamics in reading that goes beyond a directional bias – otherwise, the size of the preview effect and of the lateralization index should have been closer to equal in the two reading paradigms. From a different perspective, an existing directional bias might be actively suppressed in RSVP. Either way, in combination with the fact that the lateralized visual field advantage can be reduced by spatial cues that guide exogenous attention (Ducrot &

Grainger, 2007), our results allude to the central role of attention deployment that is also reflected in the asymmetry of the perceptual span.

Regarding the second finding of Study 3 (i.e., pre-event alpha lateralization predicted the subsequent fixation behavior from trial to trial), there was no interaction of alpha lateralization and preview that would propose attention-enabled preprocessing to be the underlying mechanism for this effect. Put differently, it did not make a difference for the prediction of fixation duration by alpha lateralization whether parafoveal information was available or not. Hence, we assume this finding to reflect general, automatic preparatory attentional processes as suggested by Romei et al. (2008). Incidentally, such preparatory attention does not have to be restricted to a pre-activation of sensory cortices, but can extend to areas specialized for language, as has been shown in fMRI studies (Van Petten, 2014). It is conceivable that the left-lateralized effect of preview on the N1 in Study 2 is somehow related to such a preparation for linguistic input. However, we can only speculate about the underlying mechanism at this point.

Unfortunately, preview itself did not modulate alpha lateralization, and neither did foveal load. In contrast to the aforementioned automatic, that is, not voluntarily driven variability in attention, the demands imposed by preview and foveal load are presumably responded to voluntarily. It is quite possible that this quick adaptation does not show in alpha lateralization. The shortcomings will be discussed further below.

3.2 Limitations and Prospects of the Three Approaches

While the probe paradigm has proven useful as a tool to map attention distribution and timing in perceptual tasks, Study 1 suggests that the implementation of the probe paradigm to reading is currently problematic. Only parafoveal inter-trial probes successfully mapped attention allocation, while parafoveal intra-trial probes did not elicit any VEPs. Since central probes were presented with the same timing as parafoveal probes, the absence of VEPs cannot be accounted for by refractoriness of the visual cortex as suggested by Bergamasco (1966) and Cigánek (1964). Instead, it is feasible that it can be attributed to a combination of insufficient stimulation at the given eccentricity and a non-additive interaction between the processing of words and probes that cannot be disentangled by the subtraction method used here (Woldorff, 1993). The overlap of ERPs at short stimulus onset asynchronies is nothing new, and in word list studies such overlap is accepted since averaging across many epochs is supposed to remove any unwanted variance. But, this overlap can be problematic if it is non-linear. In future studies, the use of deconvolution to separate overlapping potentials might offer a solution, similar to its implementation in fMRI (Dale, 1999; Dandekar, Privitera, Carney, & Klein, 2012). In this context, the development of the VESPA method seems promising (Lalor, Kelly, & Foxe, 2012; Lalor, Kelly, Pearlmutter, Reilly, & Foxe, 2007; Lalor, Pearlmutter, Reilly, McDarby, & Foxe, 2006). By constantly varying the luminance of stimuli with a temporal jitter, attention effects on these stimuli can be isolated. Instead of applying this to task-irrelevant light-flashes, words themselves could act as probes, mapping attention even more directly than previous implementations of this paradigm.

The establishment of the N1 as an electrophysiological correlate of the behavioral preview benefit is promising with regard to the investigation of parafoveal preprocessing on different processing levels such as orthographic, phonological, morphological, and semantic, all of which require attention. At this point, we cannot rule out that the preview effect reflects costs due to violated expectations about the post-saccadic retinal input (predictive coding framework; Friston, 2005; Rao & Ballard, 1999) rather than benefits due to preprocessing since the preview positivity resembles a visual mismatch negativity. However, in comparison to the probe paradigm, inferences about parafoveal attention allocation per se are only indirect. Moreover, with regard to the aim of illuminating attention dynamics in natural reading, the experimental setup utilizing word lists is not nearly as natural as necessary. First, word lists do not involve integration of neither current nor upcoming information with a prior context set by the sentence, paragraph, or even world knowledge. Second, due to this lack of context, no predictions about upcoming information can be made by the reader, which likely influences attention deployment and reciprocal eye movement such as word skipping. Third, the backward masking of words to the left of fixation does practically not allow regressions, which might lead to an unnatural adaptation of reading habits to task demands.

With regard to alpha lateralization, it has to be noted that – against our expectations – we did neither find a main effect of preview or foveal load on the lateralization index, nor an interaction effect of the lateralization index and preview on fixation behavior. In order to rule out that aggregation of the lateralization index in 300 ms bins might have concealed rapid alpha power changes that are small in amplitude, we did examine the sample-wise time course of alpha lateralization resulting from the TSE analysis, but still did not find any evidence for preview or load effects (nor any rapid attention shifts, for that matter). On the one hand, we analyzed induced band power when calculating the lateralization index. It may well be that the subtraction of the evoked portion of alpha power unintentionally diminished preview and load effects. On the other hand, the temporal resolution of alpha lateralization might be too coarse to pick up quick, voluntary (in contrast to the previously described involuntary) changes from fixation to fixation, given that there is no neutral baseline period in between (in contrast to, e.g., Perez et al., 2009) and that filtering the data introduces a small degree of temporal spread (Worden et al., 2000). Therefore, alpha lateralization does not unrestrictedly represent the desirable tool to "watch attention at work" as yet. Nevertheless, in comparison to the approach of Study 2, its use seems at least equally as promising because it did mark attention processes directly under certain circumstances rather than showing indirect consequences of attention. Note that this was the first such analysis of alpha lateralization in the comparison of saccadic and RSVP reading and that results were consistent across two re-analyzed datasets. Refining possible paradigms that are better suited for the constraints imposed by analyses in the frequency domain represents an interesting line of future research that can be nicely complemented by findings from eye movements, ERPs and FRPs.

3.3 Final Remarks and Future Directions

Considering the point of origin of this dissertation – the investigation of temporal and spatial dynamics of foveal and parafoveal attention allocation in reading, specifically within a fixation – it is eligible to draw a conclusion as regards SAS (e.g., E-Z Reader; Reichle et al., 2006) and GAG models (e.g., SWIFT; Engbert et al., 2005). Is attention allocation within a fixation strictly serial, or does a dynamically adapting gradient cover both fovea as well as parafovea, allowing simultaneous processing of words? On the one hand, the general picture generated from the three present studies points towards the latter option. (1) Parafoveal words can be completely processed while maintaining fixation if additional resources are recruited; (2) orthographic information is obtained from the upcoming word and this parafoveal preprocessing is not independent from the processing of the currently fixated word and saccade-related attention dynamics; (3) the underlying mechanism is indeed an ongoing parafoveal attention allocation.

On the other hand, all of these findings can be theoretically accounted for by SAS models, yet less parsimoniously. In any case, implications for reading models should be considered with caution since the tasks used did not involve text scanning that would normally occur during sentence reading, but rather approximated normal reading at best. Therefore, all three approaches did not yield quite sufficient implications for a clear distinction between parallel and serial models with regard to distributed processing. In fact, many findings in behavioral as well as electrophysiological research are compatible with both SAS and GAG models, from word skipping to preview effects of *n*+1 and, under some circumstances, even *n*+2 (Kliegl, Risse, & Laubrock, 2007; Schotter et al., 2012; Schotter, Reichle, & Rayner, 2014). The question is whether the distinction with regard to distributed processing is still as important as it used to be, or whether the focus has shifted to determine the circumstances under which information can be processed on different levels. For example, we found the nature and extent of parafoveal processing to be a function of the availability of cognitive resources and the time to use them, similar to Barber and colleagues (2013). They observed parafoveal congruity effects on the N400 at slow presentation rates under both high and low contextual constraints. For fast presentation rates, however, the congruity effect only occurred under high contextual constraint, indicating that the context facilitates parafoveal higher-level information extraction. Investigating early and late processing stages along those lines might specify the eye-mind link and aid in the understanding of different aspects of attention in reading. The present studies could provide further evidence for the role of attention that has been shown to cascade through several processing levels by other authors, yielding interesting contributions to the general understanding of attention dynamics in reading, as well as promising directions for future research.

3.4 Conclusion

This dissertation has investigated temporal and spatial dynamics of foveal and parafoveal attention allocation in reading using three approaches that combined eye movements and EEG. Complementary results from the present studies have provided insights into attention distribution across fovea and parafovea, its adaptation to processing load and saccadic behavior, as well as its effects on word processing. To investigate on-line visual language processing, a suitable approach must be able to handle the rapid rate of reading while capturing the dynamics of concurrent mental processing. Despite their limitations at this point, eye-movements, event- and fixation-related potentials, as well as EEG oscillations represent appropriate and promising real-time markers of attention processes in word recognition, particularly in combination.

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List of Original Articles

1. Kornrumpf, B., & Sommer, W. (2015): Modulation of the attentional span by foveal and parafoveal task load: An ERP study using attentional probes. *Psychophysiology*, *52*(9), 1218-1227. doi: 10.1111/psyp.12448

2. Kornrumpf, B.*, Niefind, F.*, Sommer, W., & Dimigen, O. (2016). Neural correlates of word recognition: A systematic comparison of natural reading and rapid serial visual presentation. *Journal of Cognitive Neuroscience*, *28*(9). doi: 10.1162/jocn_a_00977

3. Kornrumpf, B., Dimigen, O., & Sommer, W. (submitted to *Psychophysiology*): The lateralization of posterior alpha EEG reflects the distribution of spatial attention during saccadic reading.

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt,

1. dass ich die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe,
2. dass ich diese Dissertation zum ersten Mal einreiche, mich nicht anderwärts um einen Doktorgrad beworben habe und noch keinen Doktorgrad der Psychologie besitze,
3. dass mir die zugrundeliegende Promotionsordnung vom 3. August 2006 bekannt ist.

Berlin, den 22. Juli 2016

Benthe Kornrumpf